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Etude du ρ et de l'interférence ω-ρ dans le mode $\pi^+\pi^-$. Mode multipions au voisinage de 1 GeV par annihilation e^+e^-.

ARTICLE PRINCIPAL

$\pi^+\pi^-$ Production by e^+e^- Annihilation in the ρ Energy Range with the Orsay Storage Ring.

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$\pi^+\pi^-$ PRODUCTION BY e^+e^- ANNIHILATION IN THE ρ ENERGY RANGE WITH THE ORSAY STORAGE RING

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A large solid angle detector has been used to observe two body events produced by electron-positron collisions in the Orsay storage ring. From the $\pi^+\pi^-$ excitation curve in the ρ region we have deduced the amplitude and the phase of the ω-ρ interference, and the ρ resonance parameters:

$M_\rho = (775.4 \pm 7.3)$ MeV, $\Gamma_\rho = (149.6 \pm 23.2)$ MeV, $\sqrt{B(\omega \to \pi^+\pi^-)} = 0.19 \pm 0.05$, $\phi = (85.7 \pm 15.3)^\circ$, $\sigma(e^+e^- \to \rho) = (1.00 \pm 0.13)\ \mu b$ at $S = M_\rho^2$, $B(\rho \to e^+e^-) = (4.1 \pm 0.5) \times 10^{-5}$, $\Gamma(\rho \to e^+e^-) = (6.1 \pm 0.7)$ keV, $(g_\rho^2/4\pi) = 2.26 \pm 0.25$, $(g_{\rho\pi\pi}^2/4\pi) = 2.84 \pm 0.50$.

We have used a large solid angle detector $(0.6 \times 4\pi)$sr to observe both charged particles and γ rays in the decay of vector mesons produced by e^+e^- annihilation.

The apparatus is shown in fig. 1, viewed perpendicular to the beams' direction. It has a symmetry of revolution around the vacuum chamber of the ring experimental section. The interaction region of the beams is very well defined in the transverse direction (± 1mm) and spread over 15 cm in the longitudinal direction. The apparatus includes 2×16 optical spark chambers [1] and 2×15 sets of counters arranged in 6 sectors. The direction of each charged particle is measured in the first five thin spark chambers. Electron and photon showers are observed in a sandwich made of 11 lead sheets (0.5 radiation length each) interspaced between the last 11 spark chambers, as shown in fig. 2. Transverse and longitudinal views are photographed through an optical system by a single camera. A 27 cm thick lead shield above the apparatus stops all the particles coming from the beams. Counters covering this shielding are used to veto cosmic rays (anticoincidence efficiency is 99.3%). The chambers are triggered by a suitable combination of the pulses given by the scintillation counters. The two particles ($\pi^+\pi^-$ or e^+e^-) had to cross opposite sectors (AD, AE, BE, BF, CF) and, at least 6 counters had to be triggered.

The signature of the $\pi^+\pi^-$ and e^+e^- events is straightforward. Experimentally, the probability of e-π confusion has been found to be 2.5×10^{-2} for one track and hence $(2.5 \times 10^{-2})^2$ for an event This is compatible with 5 ambiguous events observed out of the 1900 $\pi^+\pi^-$ and 3100 e^+e^- events.

In each photograph we recorded counters which participated in the trigger and the timing of the trigger relative to the position of the bunches. Rejection of cosmic rays has been checked in two different ways: by trigger delay and by distance from the beams. Both methods give convergent results, to better than 1.5%; the cosmic subtraction correction is 10% at the top of ρ resonance (table 1). It was checked that all e^+e^- events had a good trigger delay.

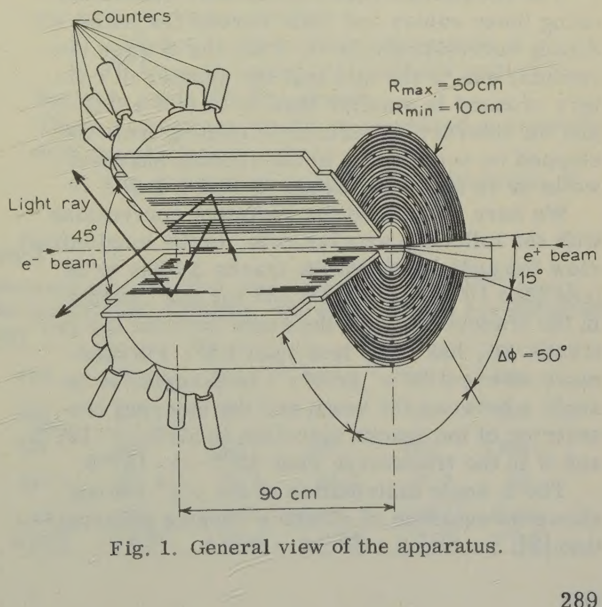

Fig. 1. General view of the apparatus.

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Table 1.
Array of the charged 2 body events versus the distance to the center of beams and the trigger delay

trigger delay (ns)	Distance from the beam (mm)									
	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5
11										
14			$\sum = 93$					$\sum = 79$		
17										
20										
23	57	33	10	2	7					
26	391	191	64	15	4			$\sum = 92$		
29	253	143	35	8	6					
32	18	10	5	2	6					
35										
38			$\sum = 92$					$\sum = 84$		
41										
44										

↔ good distance (0.5–3.5 mm); ↕ good delay (23–32 ns)

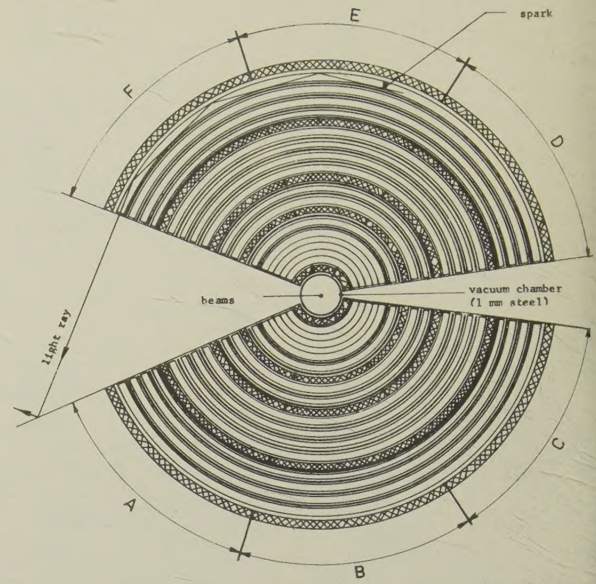

Fig. 2. Details of the apparatus (spark chamber, 21 g/cm^2 CH; counters 1 cm; lead sheet 0.5 t/x^0)

In order to make the correction for nuclear absorption of π's in the apparatus, we determined the π interaction cross section in lead and scintillator (carbon + H) from the observed interactions in our apparatus.

We find:

$$\sigma(\text{lead}) = (0.97 \pm 0.14)\sigma_{th}\,,\ \sigma(\text{carbon}) = (1.02 \pm 0.34)\sigma_{th}$$

where

$$\sigma_{th} = \pi r_0^2 A^{2/3} \text{ with } r_0 = 1.4 \times 10^{-13} \text{ cm.}$$

The interaction corrections were calculated using these values and their errors (including a strong correlation effect). Then the trigger correction, due to the fact that the number of counters crossed is smaller than 6, is $(1.3 \pm 0.2)\%$, and the interaction correction coming from the stopped or scattered π in the vacuum chamber walls or in the first counter is $(7.7 \pm 2.2)\%$.

We have calculated the radiative corrections with the following angular cuts: in the longitudinal view the angle between the tracks $\Delta\theta$ has to be less than 10^o for $\pi^+\pi^-$ and 15^o for e^+e^- events. In the transverse view the angle between the two tracks $\Delta\phi$, has to be less than 4.5^o. Furthermore an event (e^+e^- or $\pi^+\pi^-$) is accepted if the angle θ between the beam and the external bissectrice of the tracks direction is $52^o5 < \theta < 127^o5$, and if in the transverse view $22^o5 < \phi < 157^o5$.

The ϕ angle distribution of the $\pi^+\pi^-$ events shows no evidence of e^- and e^+ beams polarization [2].

The best fit of the ϕ angle distribution:

$$N(\phi) \propto 1 - \langle p_+ p_- \rangle_t \cos 2\phi$$

has given:

$$\langle p_+ p_- \rangle_t = 2.6\% \pm 4.6\%$$

perfectly compatible with no time averaged polarization.

Such an effect would change the efficiently by $0.8\% \pm 1.4\%$. This correction was not applied.

We took data at 10 energies in the ρ and ω region (table 2). The normalization was obtained from wide angle Bhabha scattering. For the radiative corrections to Bhabha scattering, we used the calculation [3] in which hard photon emission by the final lines at a large angle is taken into account.

The $\mu^+\mu^-$ pairs, which cannot be distinguished by range in our apparatus, are subtracted using the Q.E.D. cross section and the observed luminosity.

The radiative corrections for $e^+e^- \to \pi^+\pi^-$ events depend on the parametrization of the cross section and on the angular cuts: they are determined by fitting the experimental data by the convolution product of the theoretical cross section and the photon-emission probability:

$$\sigma_{exp} = \sigma_{th} * P(k)$$

where $P(k)$ is given by [4]:

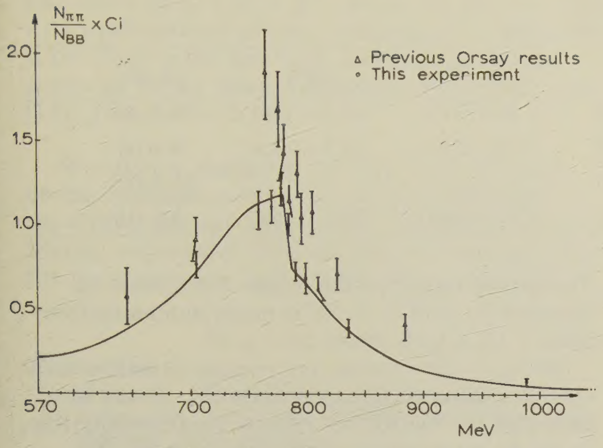

Fig. 3. Previous Orsay results compared with this experiment. The curve represents the best fit of our points (fit N° 2). (Ci is a coefficient of normalization.)

$$P(k)\mathrm{d}k = \exp\{(13/12)b\}(k/E)b(1 - \frac{k}{E} + \frac{k^2}{2E^2})\frac{\mathrm{d}k}{k}$$

with $b = 4\alpha/\pi \log(2E/m_e - \frac{1}{2})$.

At $2E = 990$ MeV the peaking approximation of radiative corrections is not accurate and we used the values given by Bonneau and Martin [5].

The theoretical cross section, σ_{th} is the coherent sum of the ρ and ω contributions. We can write it in the following way:

$$\sigma_{th} = \frac{\pi\alpha^2}{12}\frac{\beta\pi^3}{E^2}\left| F_\pi + A\exp(i\phi)\frac{M\omega^2}{M_\omega^2 - 4E^2 - i M_\omega\Gamma_\omega}\right|^2 \qquad (1)$$

where A is related to the branching ratio

$$B(\omega \to 2\pi) = \frac{\Gamma(\omega \to 2\pi)}{\Gamma(\omega \to \text{tot})} \text{ by:}$$

$$A = \frac{6\Gamma_\omega}{\alpha M_\omega \beta^{3/2}}\sqrt{B(\omega \to e^+e^-) \times B(\omega \to 2\pi)}$$

with

$$\beta = \left[1 - \frac{4m\pi^2}{M\omega^2}\right]^{1/2}$$

and ϕ is the relative phase between the two amplitudes:

$T(e^+e^- \to \rho \to 2\pi)$ and $T(e^+e^- \to \omega \to 2\pi)$.

We choose to parametrize the π form factors by a P-wave Breit-Wigner, suggested by the Gounaris-Sakurai analysis [6]:

$$F_\pi = F_0 \cdot \frac{M_\rho\ \Gamma_\rho}{M_\rho^2 - 4E^2 - i M_\rho \Gamma_\rho (P/P_0)^3 M_\rho/2E}.$$

$B(\omega \to e^+e^-)$, Γ_ω and the energy shift were determined from our $e^+e^- \to \pi^+\pi^-\pi^0$ events [7] ($\Gamma_\omega = 9.2 \pm 1$ MeV, $\Delta M_\omega = \pm 0.4$ MeV). The values of M_ρ, Γ_ρ and $B(\omega \to \pi\pi)$ depend very slightly on the values of Γ_ω and the energy shift.

We have fitted our results three different ways (table 3):

Fit 1: F_0, M_ρ, Γ_ρ, $B(\omega \to \pi\pi)$ and ϕ are free parameters.

Fit 2: the same but without using the data point at $2E = 990$ MeV, because at this energy the experimental data may be influenced by the tail of a possible ρ' resonance [8] at higher energy. Fit 2 will be used to derive the parameters of the ρ and of the ω-ρ interference.

Fit 3: with no ω-ρ interference. This fit gives a considerably larger χ^2.

In table 3 the quoted errors for the fits 1, 2, 3 are statistical only (including 1.5% due to the cosmic ray subtraction). One should add the following systematical errors (independent of energy) to the cross section:

a) 2.5% due to the nuclear absorption of π's.

b) 3% from the solid angle determination for the wide angle Bhabha events.

These two errors should ne combined quadrically with the statistical error.

c) The error coming from the calculation of

Table 2

Number of events as a function of energy ($\sigma_{\pi\pi}$ is the experimental cross section, $\sigma_{\pi\pi} = \frac{N(\pi\pi)}{N(BB)}\frac{\sigma(BB)(1+\delta_{BB})}{\epsilon}$ where ϵ is the factor including the π-interaction correction and the geometrical efficiency. the quoted errors are statistical only)

2E (MeV)	705	758	771.4	777.7	784	790.3	796.7	809.9	836	990
$N(\pi\pi + \mu\mu)$	138	182	241	306	433	268	89	107	82	197
N(BB)	269	227	284	329	541	448	154	197	213	1458
$N(\pi\pi)$	119.7	166.6	221.9	283.9	396.7	237.8	78.5	93.7	67.7	98.
$\sigma_{\pi\pi} \times 10^{30}\text{cm}^2$	0.77 ± 0.08	1.09 ± 0.11	1.12 ± 0.10	1.22 ± 0.10	1.02 ± 0.07	0.73 ± 0.06	0.69 ± 0.10	0.62 ± 0.08	0.39 ± 0.05	0.55 ± 0.01

Table 3
Summary of the four fits

Fit	F_o	M_ρ (MeV)	Γ_ρ (MeV)	$\sqrt{B(\omega\to\pi\pi)}$	$\phi(^o)$	χ^2 (d^o)
1	5.73 ± 0.23	778.5 ± 6.2	160.7 ± 16.4	0.20 ± 0.05	83.6 ± 13.4	0.7 (5)
2	5.83 ± 0.28	775.4 ± 7.3	149.6 ± 23.2	0.19 ± 0.05	85.7 ± 14.4	0.4 (4)
3	6.44 ± 0.22	763.8 ± 4.0	115.1 ± 12.5	0		11.9 (6)
4	5.95 ± 0.25	772.3 ± 5.9	135.8 ± 25.1	0.17 ± 0.05	88.3 ± 15.0	2.2 (12)

the radiative corrections of the wide angle Bhabha scattering, estimated to be 1.5%. This error must be added linearly. It should be noted that these errors are independent of the energy and therefore only affect F_o.

Finally from the following equations:

$$\sigma(e^+e^-\to\rho) = 3\pi\lambda\!\!\!^-{}^2\, B(\rho\to e^+e^-) \text{ at } S = M_\rho^2$$

where $\sigma(e^+e^-\to\rho) = \frac{\pi\alpha^2}{12}\frac{\beta_\pi^3}{E^2}|F_\pi|^2$ is the ρ contribution evaluated at $S = M^2$.

$$\Gamma(\rho\to e^+e^-) = \Gamma_\rho B(\rho\to e^+e^-)$$

$$(g^2/4\pi) = \frac{\alpha^2 M_\rho}{3\,\Gamma(\rho\to e^+e^-)}, \quad (g^2_{\rho\pi\pi}/4\pi) = 12\frac{\Gamma_\rho\to 2\pi}{\beta_\pi^3 M_\rho}$$

and from the fitted values of M_ρ, Γ_ρ and F_o (Fit 2) one derives the following values for the ρ leptonic branching ratio $B(\rho\to e^+e^-)$, the partial width $\Gamma(\rho\to e^+e^-)$, the coupling constant $g_\rho^2/4\pi$ and the $\rho\pi\pi$ coupling constant $g^2_{\rho\pi\pi}/4\pi$.

With the systematical errors included we find

$M_\rho = (775.4 \pm 7.3)$ MeV, $\Gamma_\rho = (149.6 \pm 23.2)$MeV, $\sqrt{B(\omega\to\pi^+\pi^-)} = 0.19 \pm 0.05$, $\phi = (85.7 \pm 15.3)^o$, $\sigma(e^+e^-\to\rho) = (1.00 \pm 0.13)\ \mu b$ at $S = M_\rho^2$, $B(\rho\to e^+e^-) = (4.1\pm 0.5)\times 10^{-5}$, $\Gamma(\rho\to e^+e^-) = (6.1\pm 0.7)$keV, $(g_\rho^2/4\pi) = 2.26 \pm 0.25$, $(g^2_{\rho\pi\pi}/4\pi) = 2.84 \pm 0.50$.

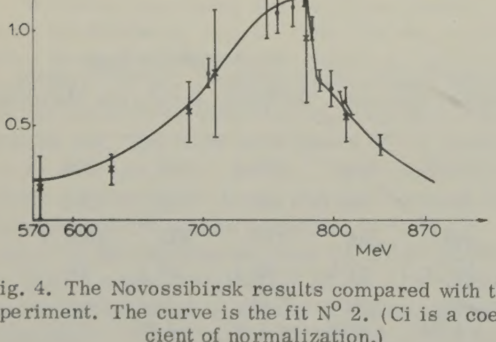

Fig. 4. The Novossibirsk results compared with this experiment. The curve is the fit N^o 2. (Ci is a coefficient of normalization.)

The quoted error on the phase ϕ includes the uncertainty ($\Delta M\omega$) of the ω mass determination; $\Delta M\omega = \pm 0.4$ MeV gives $\Delta\phi = \pm 5^o$.

In fig. 3 our results are compared with previously published Orsay results [9]. It can be seen that the two Orsay results are incompatible, so we do not present an average of these two results. The origin of this disagreement is not fully understood. What we can say is that the nuclear absorption correction (namely 22%), had been overestimated. This systematical error decreases the cross section of the previous experiment by 8%.

In fig. 4 our results are compared with the Novossibirsk results [10]. The published values of Γ_ρ, M_ρ and F_o from Novossibirsk are quite different from ours. Nevertheless, as can be seen from the agreement of the data, the discrepancy comes mainly from the analysis. They used an S-wave Breit-Wigner without ω-ρ interference. If one wants to average the results from this experiment and Novossibirsk, one must reanalyse their results. The data from such a global fit (fig. 4) using the formula (1), are given in table 3 (Fit 4).

The values of the parameters deduced from this fit are:

$M_\rho = (772.3 \pm 5.9)$ MeV, $\Gamma_\rho = (135.8 \pm 15.1)$ MeV, $\sqrt{B(\omega\to\pi^+\pi^-)} = 0.17 \pm 0.05$, $\phi = (88.3 \pm 15.8)^o$, $\sigma(e^+e^-\to\rho) = (1.04 \pm 0.12)\ \mu b$ at $S = M_\rho^2$ $B(\rho\to e^+e^-) = (4.2 \pm 0.4)\times 10^{-5}$, $\Gamma(\rho\to e^+e^-) = (5.8 \pm 0.5)$ keV, $(g_\rho^2/4\pi) = 2.38 \pm 0.18$, $(g^2_{\rho\pi\pi}/4\pi) = 2.60 \pm 0.32$.

There is a theoretical relation between g_ρ and $g_{\rho\pi\pi}$: assuming ρ dominance of the pion form factor, the vector dominance model predicts $F_o = M_\rho/\Gamma_\rho$ (with $g_\rho = g_{\rho\pi\pi}$).

When the finite width correction δ [5] is included, F_o is replaced by $(M_\rho/\Gamma_\rho)(1+\delta\,\Gamma_\rho/M_\rho)$. Gounaris and Sakurai [6] predict $\delta = 0.48$, the result from our data is $\delta = 0.66 \pm 0.39$. Gounaris and Sakurai, and also Renard [11] suggest that g_ρ and $g_{\rho\pi\pi}$ must be redefined:

$$\hat{g}^2_{\rho\pi\pi} = g^2_{\rho\pi\pi}\frac{1}{1+\delta\,\Gamma_\rho/M_\rho}, \quad \hat{g}^2_\rho = g^2_\rho(1+\delta\,\Gamma_\rho/M_\rho)$$

and hence $\hat{g}^2_{\rho\pi\pi} \equiv \hat{g}^2_0 \equiv \hat{g}^2$. From our data we find with systematical errors included, $\hat{g}^2 = 2.54 \pm 0.23$. This value has to be compared with the previous Orsay value calculated in the same way [12]: $g^2 = 2.10 \pm 0.11$.

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